# Optical discharges

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**Abstract.** — The essential features of the processes in laser radiation are considered with demonstration of their discharge nature. Review of results is given for breakdown and maintenance of continuous equilibrium plasma by laser radiation.

1. **Optical discharges and their role in comparison with other discharges.** — After development of rather powerful lasers of pulsed and continuous running many effects of laser radiation on gas and laser-plasma interaction were observed and investigated. It appears at detailed consideration that there is a number of processes which correspond to the well developed branch of physics — gas discharge physics. As a matter of fact a quite new interesting and practically important part on optical discharges is included in discharge physics, and its role is the same as radio-frequency and microwave discharge physics. The aim of this lecture is to consider the essential features of the processes in laser radiation fields, to demonstrate their discharge nature and to give a review of modern results in this field.

In pre-laser epoque (up to the middle of sixties) three main electromagnetic frequence ranges were investigated and used in gas discharge physics and technology :

1. Static electric field and close to it low frequency electromagnetic fields.

2. Radio-frequency — a wide range, with a megaherz as a middle of it.

3. Microwaves — frequences of order gigaherz, wave lengths — cm, mm.

Laser technique development gave to gas discharge physics the fourth range — an optical one, which includes infrared, visible and, to some degree, ultraviolet radiation. It is curious that in pre-laser epoque nobody could even imagine the possibility of gas discharge effects in optical fields — the usual non-laser light sources were to weak.

In order to make clear the role of effects of laser-plasma interaction in comparison with usual gas-discharge phenomena it is reasonable to classificate these phenomena. If we bear in mind the laser radiation action which is almost free of solid surface influence we should classificate these effects according to some sign which is not connected with electrode, near electrode and near wall effects. We shall distinguish three main types of volume gas discharge processes at moderate and high pressures (we consider only these pressures).

1. Gas breakdown. That is the development of ionization avalanche under action of applied external field, the conversion of initially neutral gas into plasma.

2. The maintenance of non-equilibrium plasma. In this case the temperature of electrons responsible for ionization is rather high but gas of heavy particles remains cold. Usually it is weakly ionized plasma at moderate pressures, less than hundreds of torr.

| Field frequency range | Discharge plasma-type: Breakdown | Non-equilibrium plasma maintenance | Equilibrium plasma maintenance |
|---|---|---|---|
| Static electric field | Discharge gap breakdown | Positive column of glow discharge | Positive column of arc discharge |
| Radio frequencies | *Rf* breakdown | Radio-frequency capacity discharge at moderate pressure | Induction discharge at atmospheric pressure |
| Microwave frequencies | Breakdown in wave-guides and resonators | Pulse discharge in wave-guides and resonators | Microwave plasmatron |
| Optical radiation | Gas breakdown by laser radiation | The late stage of optical breakdown | Continuous optical discharge |

3. The maintenance of equilibrium plasma by e.m. field : electron and heavy particle temperatures are almost equal, ionization degree is close to its thermodynamically equilibrium value. This is so called low temperature plasma with temperatures of order of 10 000 K of atmospheric pressures.

Each of these three processes can be realised in fields of any of four listed ranges. And, actually the most part of these phenomena was observed experimentally and investigated in detail. The following table explains the above given classification. Here the typical conditions under which one or another process occurs are pointed out.

Considering optical discharges in more details we can see that these phenomena do not differ, in principle from corresponding discharge processes at other frequency ranges. So one can doubtless put optical discharges into above given table.

2. **Optical gas breakdown.** — This effect was discovered in 1963 [1]. The beam of $Q$-switched ruby laser was focused by lens, there was a spark in the focal region where plasma was formed. To achieve gas breakdown by light radiation one need to have high laser parameters. The atmospheric air breakdown occurs at peak power of 30 MW (pulse energy 1 J, pulse duration 30 ns) and the focal region radius $10^{-2}$ cm. Radiation intensity at focal region is about $10^5$ MW/cm$^2$, and electric field in e.m. wave about

$$6 \times 10^6 \text{ V/cm}.$$

Breakdown threshold is very sharp, and when radiation intensity is decreased to some value the breakdown ceases to exist.

New effect is of great interest for physicists. For some years optical breakdown was investigated experimentally and theoretically in so detailed manner that now we know about it not less than we know about its analogue — microwave breakdown — and at least more than we know about much more complicate process — breakdown in electrode gap.

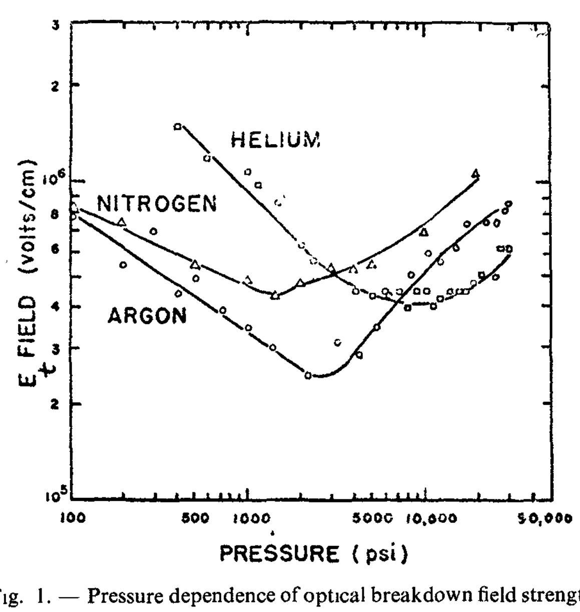


Fig. 1. — Pressure dependence of optical breakdown field strength.

The main results on optical breakdown were obtained in sixties. The theoretical explanation of this phenomenon was given at the same time. All these results are well known, they are summarized in [2]. The recent years don't add any significant results — some additional experimental values, the understanding of more fine details, more precise theoretical explanations.

The threshold fields in light wave $E_t$ necessary for breakdown by focused radiation of ruby laser are shown at figure 1 (from [3]) for a few gases. The thresholds were measured in wide pressure intervals. The similar data on microwave breakdown is given at figure 2 (from [4]) for comparison. Note the resemblance of dependencies $E_t(p)$. As we shall see this resemblance has deep physical foundations.

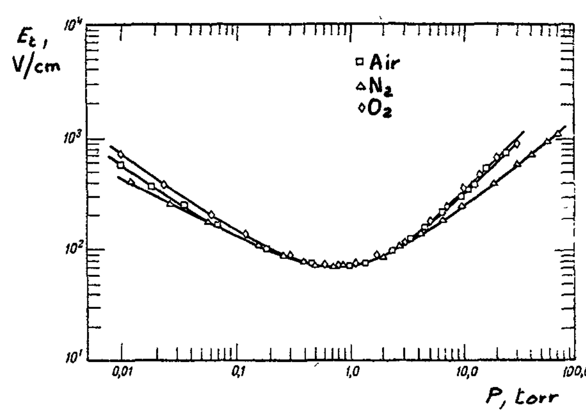


Fig. 2. — Pressure dependence of microwave breakdown field strength. Frequency 994 MHz, diffusion length 1.51 cm.

The electron avalanche is developed under action of light electromagnetic field in the same manner as in other fields. The first *seed* electrons appear in the light wave field as a result of multiphoton photoelectric effect. This is different from the cases of other fields where the *seed* electrons appear by randomly chance (from cosmic radiation). In the wave field the electron acquires its energy gradually at collisions with atoms till this acquired energy would be sufficient for atom ionization and new electron appear. In such a way the electron reproduction occurs. The avalanche development is determined by the processes of electron energy increase in the electromagnetic field and electron energy losses at collisions (elastic and non-elastic ones), and also by the electron losses because of diffusion or electron attachment in electronegative gases.

The losses of electron energy and losses of electrons themselves depend weakly on the field nature and it happens more or less in the same way in any fields. Only energy increase depends on field frequency and the peculiarities of optical discharge are

connected with quantum nature of interaction between electrons and optical e.m. field. According to classical theory an electron in oscillating field oscillates and at the same time moves randomly. At every collision its average vibration energy

$$\varepsilon_{osc} = e^2 E^2/m\omega^2$$

transforms into energy of random motion ($E$ — mean square field, $\omega$ — frequency). The rate of energy increase from field is equal to

$$\left(\frac{d\varepsilon}{dt}\right)_E = \frac{e^2 E^2}{m(\omega^2 + \nu_m^2)} \nu_m \qquad (1)$$

where $\nu_m$ effective frequency of electron-atom collisions. In the case when electron does not manage to make many oscillations during the time between collisions the energy acquired at collision is decreased in comparison with the energy $\varepsilon_{osc}$ and we have to use $\omega^2 + \nu_m^2$ instead of $\omega^2$. The relation (1) is valid even in the limit of static field at $\omega \to 0$.

From (1) one can see that for any frequency at rather low pressures when $\nu_m^2 \ll \omega^2$, the low of proportionality $(d\varepsilon/dt)_E \sim E^2 \nu_m/\omega^2$ is valid. The rate of energy increase is determined by the ratio $E/\omega$. The rate is the more the higher the pressure. To the contrary, at high pressures when $\nu_m^2 \gg \omega^2$, the rate $(d\varepsilon/dt)_E \sim E^2/\nu_m$ is decreased with pressure and it does not depend on $\omega$. In order an avalanche and breakdown take place it is necessary to overcome the electron and electron energy losses. That definite rates of energy increase in the field $(d\varepsilon/dt)_E$ and definite ionization frequency are required. The required ionization frequency depends on $(d\varepsilon/dt)_E$.

It follows from this fact that at $\nu_m^2 \ll \omega^2$ the threshold field is proportional to the frequency and decreases when the pressure increases. At rather high pressures when $\nu_m^2 \gg \omega^2$ the threshold field depends weakly on the frequency and, to the contrary, increases with pressure. At pressures satisfying the condition $\nu_m \approx \omega$, the function $E_t(p)$ has a minimum. The figure 2 for microwave breakdown can be explained by these considerations. In the same quality manner one can explain optical breakdown curve (Fig. 1). The relation (1) makes clear why at optical frequencies it is necessary for breakdown to have much higher fields than at microwave frequencies ($E_t \sim \omega$; threshold wave intensity $S_t \sim E_t^2 \sim \omega^2$). It is clear why minimum of $E_t(p)$ moves in the direction of very high pressure region (hundreds of atmospheres). The minimum corresponds to

$$\nu_m = \text{constant}\, p \approx \omega\,.$$

The question is how to ground the applicability of relation (1).

In one of the first papers on optical breakdown [5] the possibility to apply approximately this simple and convenient relation was shown. The quantum theory of the effect was also constructed in this paper. In fact, in light field an electron absorbs energy quanta $\hbar\omega$, equal to 1.78 eV in the ruby laser case. It is much more than average energy of electron oscillations in the wave field $\varepsilon_{osc} = e^2 E^2/m\omega^2$. However the analysis of kinetic equation for energy distribution function shows that formula (1) is valid not only under the condition $\hbar\omega \ll \varepsilon_{osc}$, but under weaker condition $\hbar\omega \ll \varepsilon$. In microwave region even trivial requirement $\hbar\omega \ll \varepsilon_{osc}$ is satisfied and there is no question on quantum effects. In optical range we have $\varepsilon_{osc} \sim 10^{-2}$ eV $\ll \hbar\omega \approx 1.8$ eV. But average energy of electron spectrum is of order of ionization potential, that is 10 eV, therefore one can consider the condition $\hbar\omega \ll \varepsilon$ to be satisfied.

In the case of optical fields the formula (1) is approximately valid but one has to treat it statistically. Let, for example $\varepsilon_{osc} = 0.01\, \hbar\omega$. Of course an electron can not acquire 1/100 of quantum energy from field during a collision. It means roughly that it does not acquire any energy during 99 collisions and acquires an energy quanta at hundredth collision. The precise calculations of electron avalanche and breakdown threshold are made as usually on the base of kinetic equation. The calculations of paper [5] and the following ones are in agreement with experimental results.

The fact that the relation $S_t \sim \omega^2$ is satisfied for threshold radiation intensity in wide frequency range from microwave ($\omega \sim 10^{10}$ rad/s) up to optical frequencies ($\omega \sim 10^{15}$ rad/s) is a significant argument in favour of avalanche theory. The data on optical breakdown at some frequencies of visible and infrared spectrum parts (ruby, neodymium and $CO_2$-laser) are available. Quite recently the data on the widest range between microwave and infrared spectrum parts were obtained. The breakdown by radiation with wave length $\lambda = 0.38$ mm was investigated, the radiation source being a laser on heavy water. Figure 3

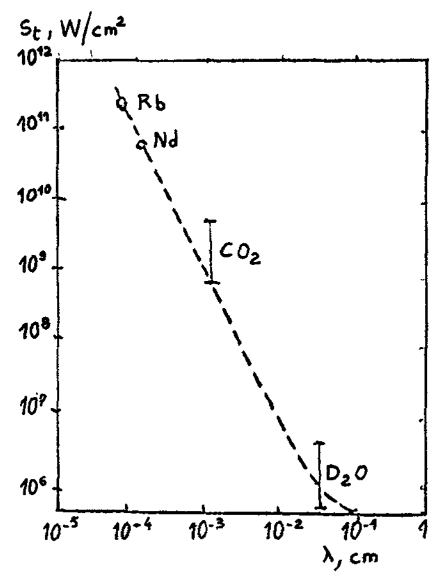


Fig. 3. — Frequency dependence of breakdown.

demonstrates the curve $S_t \sim \omega^2$. The apparent deflection in low frequency region is because of the fact that one has to put the value of $\omega^2 + \nu_m^2$ instead of $\omega^2$ into formula (1). Taking into account this fact one can diminish a disagreement. The real deflection from the curve $S_t \sim \omega^2$ is observed in ultraviolet spectrum part, at breakdown by second harmonics of neodymium and ruby lasers where quantum effects are significant (second harmonics ruby quanta is very high — $\hbar\omega = 3.56$ eV).

The consideration given shows that effects of optical and microwave breakdown have much in common. There are, of course, some new details connected with quantum nature of interaction between light radiation and matter. For example the ionization of excited atoms is possible by two or three-photon effect and sometimes it is of essential influence on electron reproduction rate. But in the main, optical breakdown mechanism is not different from mechanism of volume (not streamer) breakdown in any other fields.

3. **The maintenance of non-equilibrium plasma.** — This process is usual in the static field — glow discharge. But it is not typical not only for optical but even for microwave frequencies. The matter of the fact is that plasma can be a non-equilibrium one only as weakly ionized and when the pressures does not high. Energy input must be small and energy exchange between electrons and heavy particles must be very slow. Otherwise gas is quickly heated, achieves an equilibrium with electrons and ionization is a thermal one. But at very low gas densities plasma absorbs light radiation weakly, therefore steady-state non-equilibrium plasma maintenance in laser radiation field would require great laser power.

Even in microwave frequency where coefficient of electromagnetic field absorption proportional to $1/\omega^2$ is high, one can obtain a non-equilibrium plasma only in pulse fields, when high radiation intensities are possible. In steady-state microwave one can obtain only equilibrium highly ionized plasma at normal pressure conditions.

One can obtain non-equilibrium plasma at late stage of optical breakdown, but such effects did not attract attention of theoreticians and experimentators. Therefore we consider the third (according to classification adopted) type of discharge processes.

4. **The maintenance of equilibrium plasma in continuous optical discharge.** — The arc-like discharges in which steady-state equilibrium plasma is maintained by e.m. field are widely applied in physical experiments and technology. The generators of dense low-temperature plasma are operating on this base. In plasmatron the cold gas flows through the region of the steady-state burning discharge. Passing the discharge region gas flows out as a continuous plasma jet usually at normal pressure conditions. Now the e.m. fields of three frequency ranges (static, *r-f* and microwave) are used in industrial plasmatrons. There are arc, inductive and microwave plasmatron, respectively.

In 1970 the possibility of steady-state plasma maintenance by light radiation of continuously operating laser was grounded theoretically as well as the possibility of optical plasmatron creation [7]. In the same year continuous optical discharge (as it was called) was obtained experimentally by means of continuously operating $CO_2$-laser [8].

It does not differ from steady state equilibrium discharges in other fields. Plasma energy losses because of heat conductivity and thermal radiation are balanced by light wave energy absorption. Plasma achieves such a temperature (it determines the light absorption coefficient) in order to compensate exactly energy input and energy losses and secondly to stabilisate stationary plasma state.

Plasma maintenance by laser radiation has its own peculiarities connected with the properties of opical frequency range of e.m. field. The main feature is the possibility of distant energy transfer. To transfer energy in any other field one requires some constructive elements : electrodes in arc discharge, solenoids — in *r-f* field, waveguide — in microwave but one can transfer laser beam to plasma directly through air. This makes possibly to initiate an optical discharge at unreachable places, in the free air. One can make plasma to move in space by moving light beam. It is possible to obtain optical plasmatron by gas flow through discharge.

In practice, one can obtain continuous optical discharge focusing laser beam by lens or mirror. Plasma is produced in the focal region where light intensity is high. It moves to radiations source up to light cone section where light intensity is high enough to maintain gas discharge (Fig. 4).

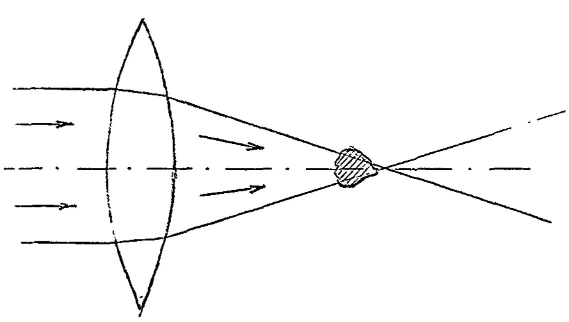

Fig. 4. — Sketch of experiment on continuous optical discharge.

In order to ignite discharge, it is necessary to create the initial plasma at the focal region by any manner. It is convenient by example, to put here the piece of metallic wire in short time.

The main problem of equilibrium discharge theory

is to determine plasma temperature as a function of applied field parameters. Generally the problem is solved on the base of equation set describing plasma-field energy balance. Let us consider a simple model. We shall simulate a focused laser beam by means of spherically convergent radiation flux with power $P_0$. A fraction of radiation power $P_1$ is absorbed by plasma generated in central region. Plasma temperature $T(r)$ decreases monotonically from its maximal value $T_k$ in the centre and this value $T_k = T(0)$ is plasma temperature characteristics. We neglect energy losses due to thermal radiation. Energy flux due to heat conductivity can be written in the following form

$$J = -\lambda\, \mathrm{d}T/\mathrm{d}r = -\,\mathrm{d}\theta/\mathrm{d}r\,, \quad \theta = \int_0^T \lambda\, \mathrm{d}T \qquad (2)$$

where $\lambda$ heat conductivity, and $\theta$ heat flux potential.

The coefficient of light absorption by plasma $\mu_\omega$ depends sharply on temperature through such kind dependence of gas ionization degree. Introduce some ionization temperature $T_0$ in such a way that for temperatures less than this value ionization is so weak that one can neglect light absorption. Let $r_0$ — is a radius of a sphere where $T = T_0$. Outside the absorbing sphere the whole heat flux through sphere surface does not depend on radius :

$$4\,\pi r^2 J = P_1 = \text{constant}\,.$$

This gives $\theta(r) = P_1/4\,\pi r$ and

$$P_1 = 4\,\pi r_0\, \theta_0\,, \quad \theta_0 \equiv \theta(T_0)\,. \qquad (3)$$

One can approximately write the following expression for energy balance inside of absorbing sphere

$$P_1 \approx 4\,\pi r_0^2\, \Delta\theta/r_0 = 4\,\pi r_0\, \Delta\theta\,, \quad \Delta\theta = \theta_k - \theta_0 \qquad (4)$$

where $\Delta\theta$ — the difference of heat flux potential between centre of sphere and plasma boundary and

$$\theta_k \equiv \theta(T_k)\,.$$

It follows from the relations (3) and (4), that

$$\Delta\theta \approx \theta_0 \approx \frac{\theta_k}{2}\,. \qquad (5)$$

Usually optical thickness of plasma is small. In this case the light absorption is not full and the absorbed energy is of order of $P_1 \approx \mu_\omega r_0 P_0$, where absorption coefficient corresponds to characteristic plasma temperature $T_k$. Combining this relation with (4) and (5) we find the relation between plasma temperature $T_k$ and incident radiation power $P_0$

$$P_0 \approx \frac{2\,\pi\theta(T_k)}{\mu_\omega(T_k)}\,. \qquad (6)$$

At constant pressure the function $\mu_\omega(T)$ grows very sharply, then begins to fall. Maximum $\mu_\omega(T)$ corresponds to almost full single ionization of atoms. When temperature increases farther ionization degree changes slowly till the second ionization begins, electron and ion density being decreased because of

$$p \sim nT = \text{constant}\,.$$

As a result the coefficient $\mu_\omega \sim n_e n_t \sim n^2$ falls. The dependence $\theta(T)$ grows monotonically therefore $P_0$ as a function of $T_k$ possesses a minimum (see Fig. 5). Minimum $P_{0\,\mathrm{min}} \equiv P_t$ is in a region of maximum of $\mu_\omega(T)$, that is at temperature which corresponds to almost full single ionization of atoms.

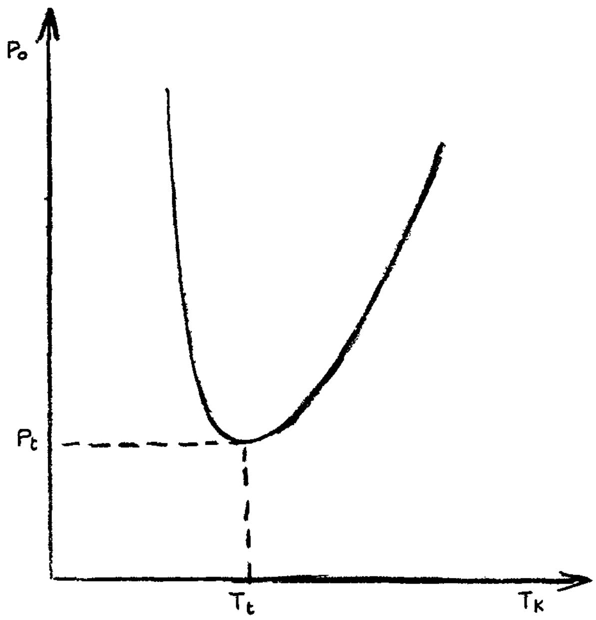


Fig. 5. — Laser power as function of plasma temperature in continuous optical discharge.

There is no steady-state regime at powers $P_0 < P_t$. The value $P_t$ is a minimal threshold power at which continuous optical discharge is possible. The higher is gas pressure the lower is threshold power, because at high pressures light absorption coefficient is more. The threshold is lower when gas have bad heat conductivity also.

The first experiments on continuous optical discharge were made in weakly heat-conductive gas, xenon, at pressures of a few atmospheres. Low-power $CO_2$-laser was required, only 150 W. In further experiments plasma was produced by means of more powerful lasers in many gases and at atmospheric pressure. In order to maintain discharge in atmospheric air the minimal radiation power of $CO_2$-laser is required, $P_t \approx 2.2$ kW. Plasma temperature is $T_k = T_t = 18\,000$ K, $\theta_k \approx 0.3$ kW/cm,

$$\mu_\omega(T_k) \approx 0.85\ \mathrm{cm}^{-1}$$

Plasma radius $r_0$ is of order of 1 mm but to estimate this one need more detailed considerations [2].

When laser power increases plasma temperature grows slowly, but the region occupied by plasma grows more rapidly. This process corresponds to the right branch of curve $P_0(T_k)$ (see Fig. 5). The left branch at which $T < T_t$, corresponds to unstable states. Actually if plasma temperature randomly rises one need lower power to maintain plasma. The heating begins and representative point of gas state travels to the right branch, to the temperature point corresponding to the same power. The situation of optical discharge does not differ from the situations in other equilibrium discharges [2].

A continuous optical discharge in atmospheric air was investigated by means of 5-6 kW $CO_2$-lasers [9, 10] and experimental results confirmed the above given estimation of threshold power. Experimental threshold value is equal to 2 kW. The measured spatial distributions of temperature and power absorption coefficients are shown at figures 6, 7. Maximal measured parameters $T = 15\,000$ K, $\mu_\omega = 0.7\ \mathrm{cm}^{-1}$ also are in agreement with above given estimation. As it was measured [10], plasma temperature in centre of air discharge was equal to $T \approx 17\,000$ K plasma temperature in argon discharge was equal to 23 000 K at $p = 2$ atm [11]. This heated plasma may be considered as a very high brightness light source of continuous action and this gives great possibilities for different applications.

The temperature in an optical discharge plasma is much higher than in other equilibrium discharges where it does not exceed 10 000 K. The reason is that in the low frequency region plasma absorbs field energy even at weak ionization. Electromagnetic field cannot penetrate into highly ionized gas and this is because the condition for energy release becomes worse and plasma temperature cannot rise highly.

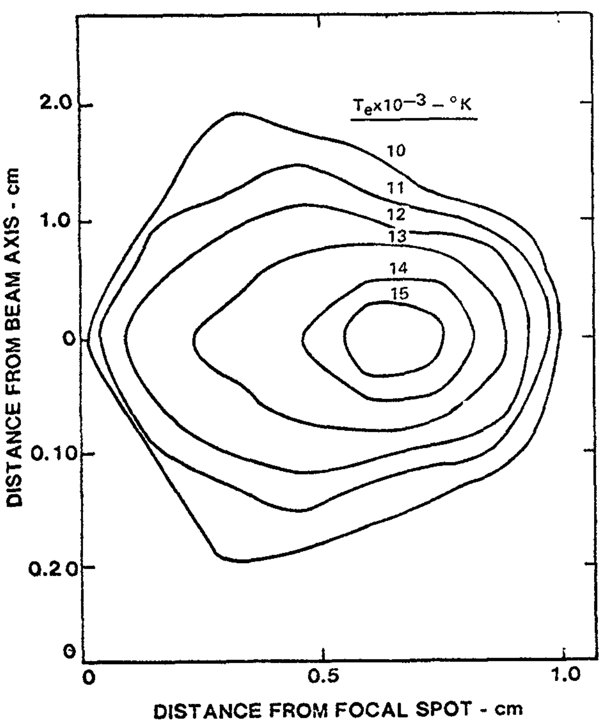


Fig. 6. — Spatial distribution of electron temperature in continuous optical discharge. Incident $CO_2$-laser power 3.5 kW.

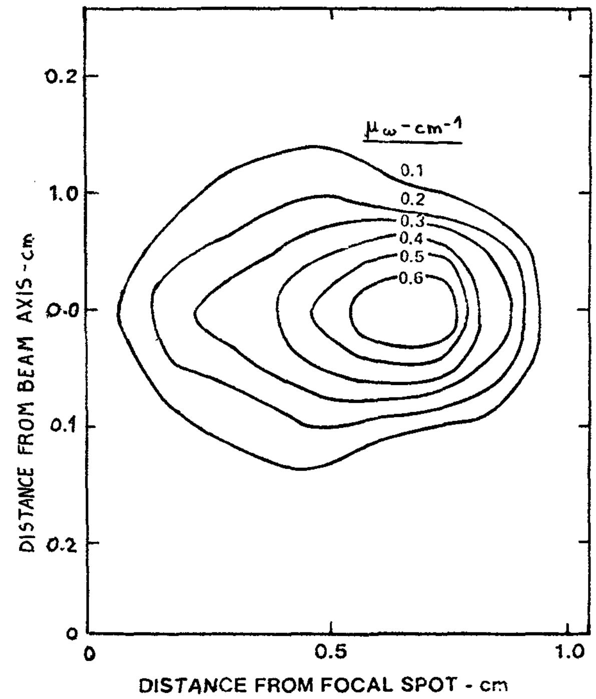


Fig. 7. — Spatial distribution of absorption coefficient. Incident $CO_2$-laser power 3.5 kW.

In optical frequency range plasma absorbs weakly because of high field frequency ($\mu_\omega \sim \omega^{-2}$). The best field dissipation occurs in fully single ionized plasma and this is why gas is so heated. The unique optical discharge property — extremely high plasma temperature.

At high pressures of order of 10 atm and higher the energy losses because of thermal radiation exceed the heat conductivity losses. As in the case of high pressure arcs, in optical discharge there is an effective conversion of laser radiation energy into the energy of thermal radiation of rather high temperature [12].

A continuous optical discharge was obtained experimentally in argon jet at atmospheric pressure [13] and it can be considered as optical plasmatron. A continuous optical discharge is sometimes generated at irradiation of metal surfaces by rather intense $CO_2$-laser radiation. Plasma is produced in air, in front of the surface. The surface absorbs a noticeable part of incident radiation, and as a result the surface is shielded from radiation. It makes the difficulties in the surface treatment by laser radiation.

5. **Optical discharge propagation.** — In any frequency region the discharges exhibit a tendency to propagate. Always there are mechanisms of energy transfer from discharge plasma to the surrounding

layers of cold gas. This makes a contribution into ionization. If just ionized layer is in external field, field energy dissipation begins. The layer is captured by discharge. The same situation is repeated the next layer and so on. Discharge boundary propagates through gas. The discharge is a static one if the walls enclosing the discharge volume prevent to its propagation or field intensity outside the discharge is not high enough to maintain plasma.

Different mechanisms are possible to transfer energy and ionization from discharge plasma to neighbour cold layers, namely, by shock waves, heat conductivity, thermal radiation. Resonance radiation diffusion, electron diffusion, also contribute into ionization process. As an example of discharge propagation one can consider a process in plasmatron, but in this case one observes reversed picture of propagation. The cold gas flows through non-moving discharge and is ionized. In the coordinate system connected with cold gas flow the discharge boundary is propagated through gas. The usual mechanism of propagation in plasmatron is the heat conductivity accompanied by thermal ionization of cold gas.

Plasma motion in the laser radiation field belongs to the phenomena of discharge propagation. It was discovered soon after the laser spark observation. Plasma boundary of optical discharge travels to the source of incident laser beam from focal point with the velocity of order of 100 km/s. In this case the mechanism of plasma propagation is a shock wave. This effect is similar to the explosive detonation and is treated as a *light detonation*. This phenomenon was widely investigated both theoretically and experimentally (see [2]). It is interesting to note that discharge propagation by shock wave was observed only for optical frequencies, after gas breakdown by giant pulses of laser radiation. Probably the similar process is not possible in other fields at all, because very high intense fields are necessary for detonation, and in any other fields the breakdown occurs earlier than *detonation* wave.

There were many investigations of the other effect — optical discharge propagation by means of heat conductivity. This process has much in common with deflagration.

Plasma front moves to meet a laser beam and its velocity is of order of 1-10 m/s. Usually discharge propagates through plasma by means of heat conductivity, energy transfer by thermal radiation may be also of importance in propagation processes. In experiments one observes sometimes that propagation velocity is a sum of plasma front velocity relatively the gas and of gas velocity. Plasma expands and pushes cold gas — discharge front propagates in moving gas. One can find the more detailed consideration of *light deflagration* in [2]. One can also mention more recent papers [13-15].

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